BSM Searches at Electron-Proton Colliders Overview

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on behalf of the BSM@ep group
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Karlsruher Institut für Technologie

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Introduction

- Electron-proton collider ideal laboratory to study common features of electrons and quarks with EW / VBF production, LQ,multi-jet final states, forward objects
- Broad BSM program at the FCC-eh in terms of exploration of new and/or challenging scenarios
- Differences and complementarities: characterization of new physics from hints at ee and pp colliders
- Promising aspects:
  - Small background (no QCD interaction between e and p)
  - Very low pileup
- Difficult aspects: low production rates for new physics processes due to small $\sqrt{s}$
- Lately, great engagement from theory community working with experimentalists

A wide program of searches is on going....

number	general
1	Acar, Y. C., Akay, A. N., Beser, S., Karadeniz, H., Kaya, U., Oner, B. B., & Sultansoy, S., FCC Based Lepton-Hadron and Photon-Hadron Colliders: Luminosity and Physics., http://arxiv.org/abs/1608.02190
	SUSY (general)
2	Han, C., Li, R., Pan, R.-Q., & Wang, K. , Searching for the light Higgsinos at the CERN LHeC., http://arxiv.org/abs/1802.03679
3	S. Kuday, Resonant Production of Sbottom via RPV Couplings at the LHeC https://arxiv.org/abs/1304.2124
4	Hong-Tang, W., Ren-You, Z., Lei, G., Liang, H., Wen-Gan, M., Xiao-Peng, L., & Ting-Ting, W., Probe R-parity violating stop resonance at the LHeC, http://lanl.arxiv.org/abs/1107.4461
	Long-lived particles - SUSY and beyond
5	Curtin, D., Deshpande, K., Fischer, O., & Zurita, J., New Physics Opportunities for Long-Lived Particles at Electron-Proton Colliders. http://arxiv.org/abs/1712.07135
	heavy/sterile neutrinos
6	Duarte, L., Zapata, G., & Sampayo, O. A., Angular and polarization trails from effective interactions of Majorana neutrinos at the LHeC., http://arxiv.org/abs/1802.07620
7	Antusch, S., Cazzato, E., & Fischer, O. Sterile ,neutrino searches at future e^-e^+, pp, and e^-p colliders,, http://arxiv.org/abs/1612.02728
8	Duarte, L., González-Sprinberg, G. A., & Sampayo, O. A., Majorana Neutrinos Production at LHeC in an Effective Approach, http://xxx.lanl.gov/abs/1412.1433
	anomalous couplings, Effective Lagrangian
9	Kuday, S., Saygin, H., Hos, I., & Cetin, F., Limits on Neutral Di-Boson and Di-Higgs Interactions for FCC-he Collider., http://arxiv.org/abs/1702.00185
10	Cakir, I. T., Cakir, O., Senol, A., & Tasci, A. T., Search for Anomalous WW\gamma and WWZ Couplings with Polarized e-Beam at the LHeC, Acta Physica Polonica B, 45(10), 1947 (2014) https://doi.org/10.5506/APhysPolB.45.1947
	BSM Higgs:
11	Azuelos, G., Sun, H., & Wang, K., Search for Singly Charged Higgs in Vector Boson Scattering at the ep Colliders., http://arxiv.org/abs/1712.07505, see also K. Wang and H Sun: talk at Sept. 2017 workshop
12	Sun H, Luo X, Wei W, Liu T., Searching for the doubly-charged Higgs bosons in the Georgi-Machacek model at the ep colliders, Phys. Rev. D 96, 095003
	compositeness, contact interactions, excited/heavy fermions,GUT
13	Zarnecki: arXiv:0809.2917, hep-ph/0104107
14	see also new limits from HERA: Zeus Collaboration, 1604.01280 and Zarnecki, 1611.03825
15	Liu, Y.-B., Search for single production of vector-like top partners at the Large Hadron Electron Collider., http://arxiv.org/abs/1704.02059
16	Lindner, M., Queiroz, F. S., Rodejohann, W., & Yaguna, C. E., Left-right symmetry and lepton number violation at the Large Hadron electron Collider., Journal of High Energy Physics, 2016(6), 140., https://doi.org/10.1007/JHEP06(2016)140
17	Mondal, S., & Rai, S. K., Polarized window for left-right symmetry and a right-handed neutrino at the Large Hadron-Electron Collider, Physical Review D, 93(1), 11702. (2016) https://doi.org/10.1103/PhysRevD.93.011702
	top quark FCNC and anomalous couplings (top group)
18	http://arxiv.org/abs/1701.06932, Denizli H, Senol A, Yilmaz A, Cakir IT, Karadeniz H, Cakir O., Top quark FCNC couplings at future circular hadron electron colliders
19	http://arxiv.org/abs/1703.02691, Wang X, Sun H, Luo X., Searches for the Anomalous FCNC Top-Higgs Couplings with Polarized Electron Beam at the LHeC
20	http://arxiv.org/abs/1705.05419, Cakir IT, Yilmaz A, Denizli H, Senol A, Karadeniz H, Cakir O., _Probing the Anomalous FCNC $tq\gamma$ Couplings at Large Hadron electron Collider
21	Sarmiento-Alvarado, I. A., Bouzas, A. O., & Larios, F., Analysis of the top-quark charged-current coupling at the LHeC, http://arxiv.org/abs/1412.6679
22	Dutta, S., Goyal, A., Kumar, M., & Mellado, B., Measuring anomalous Wtb couplings at e^-p collider, http://arxiv.org/abs/1307.1688
	exotic and miscellaneous
23	Acar, Y. C., Kaya, U., Oner, B. B., & Sultansoy, S., Color Octet Electron Search Potential of the FCC Based e-p Colliders, http://arxiv.org/abs/1605.08028
24	Hernandez-Sanchez, J., Das, S. P., Moretti, S., Rosado, A., & Xoxocotzi, R., Flavor violating signatures of neutral Higgs bosons at the LHeC, http://arxiv.org/abs/1509.05491
25	Das, S. P., Hernández-Sánchez, J., Rosado, A., & Xoxocotzi, R., Flavor signatures of lighter and heavier Higgs bosons within Two Higgs Doublet Model type III at the LHeC, http://arxiv.org/abs/1503.01464
26	Sahin, M., Resonant Production of Spin-3/2 Color Octet Electron at the LHeC. Acta Physica Polonica B, 45(9), 1811 (2014), https://doi.org/10.5506/APhysPolB.45.1811
27	Ren-You, Z., Hua, W., Liang, H., & Wen-Gan, M., Probing L-violating coupling via sbottom resonance production at the LHeC, http://lanl.arxiv.org/abs/1401.4266
	Leptoquarks
28	Zhang J, Yue C-X, Liu Z-C, Signals of the first generation scalar leptoquarks at LHeC, Mod.Phys.Lett. A33 (2018) no.06, 1850039

Overview

Selective:

- BSM Higgs sector
- SUSY (R parity violating and conserving)
- Longlived particles
- Sterile neutrinos
- Leptoquarks

Aim of this talk:

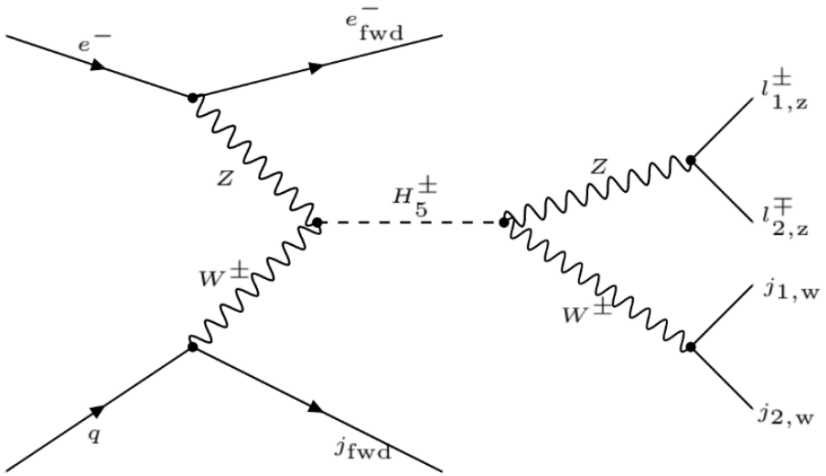
$\rightarrow$ Report on most recent studies and progress

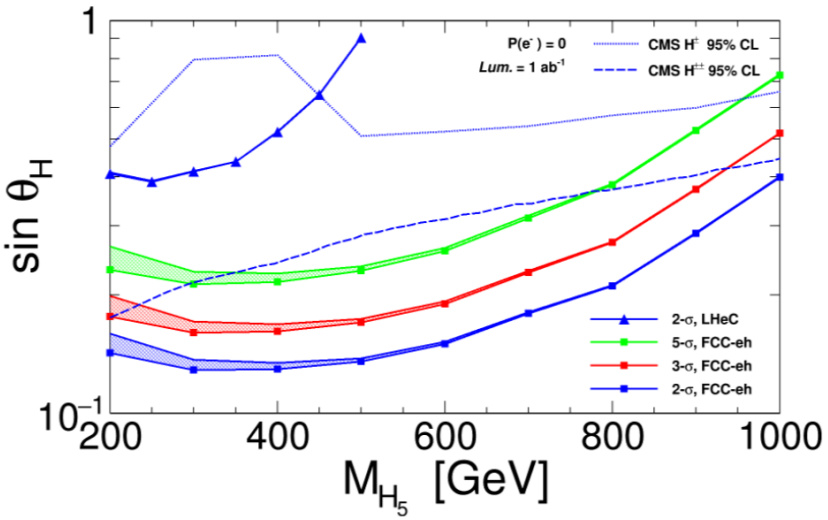
$\rightarrow$ Brief overview of previously finalized studies

$\rightarrow$ Encourage future studies and synergies

BSM Higgs sector

$H^{\pm}$, $H^{\pm\pm}$ in Vector Boson Scattering





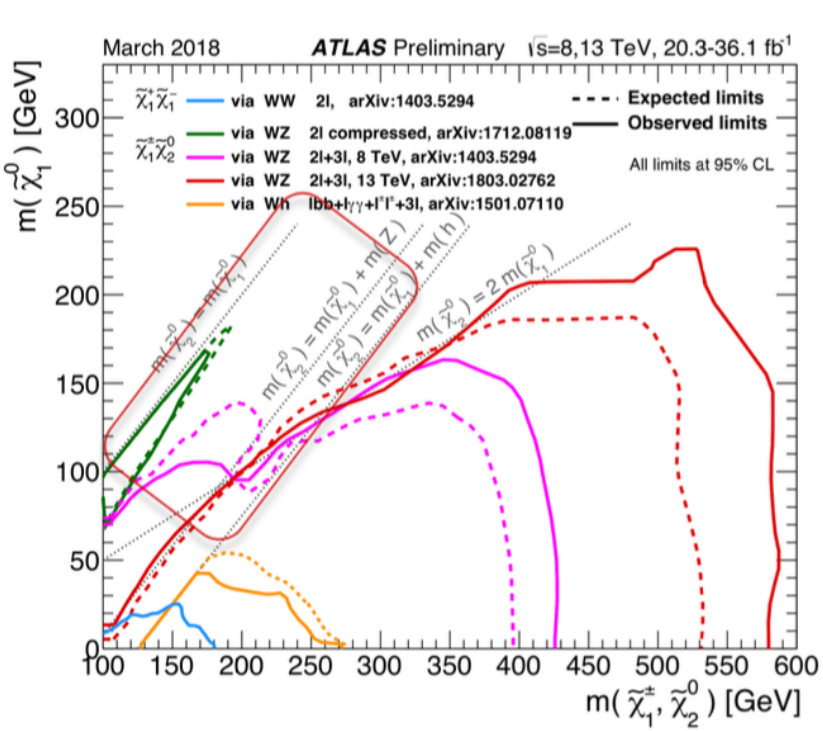
Azuelos, Sun, Wang; [arXiv:1712.07505]

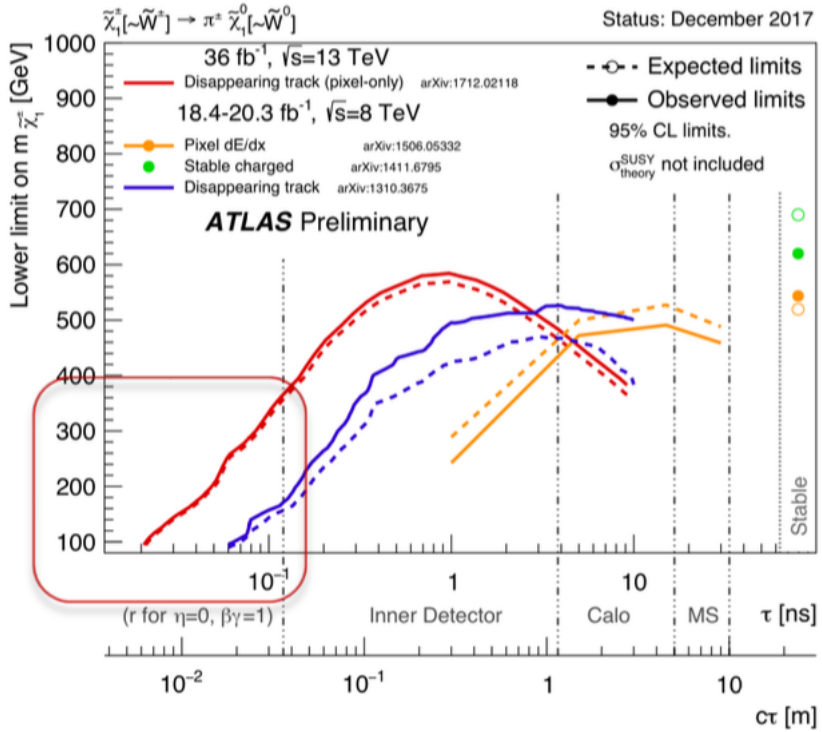
Georgi-Machacek Model:

- No fundamental reason for a minimal Higgs sector
  $\Rightarrow$ Extension with higher isospin multiplets
- Has a custodial symmetry (i.e. ρ parameter $= 1$)
- Might generate Majorana mass for neutrinos via type II seesaw mechanism
- Mass eigenstates: $H_5^{\pm\pm}, H_5^{\pm}, H_5^0$, two parameters: m_{H_5}, $\sin\theta_H$.
- H_5 decays almost exclusively to gauge bosons

Electroweak SUSY sector

Compressed scenarios most challenging for searches at pp colliders:

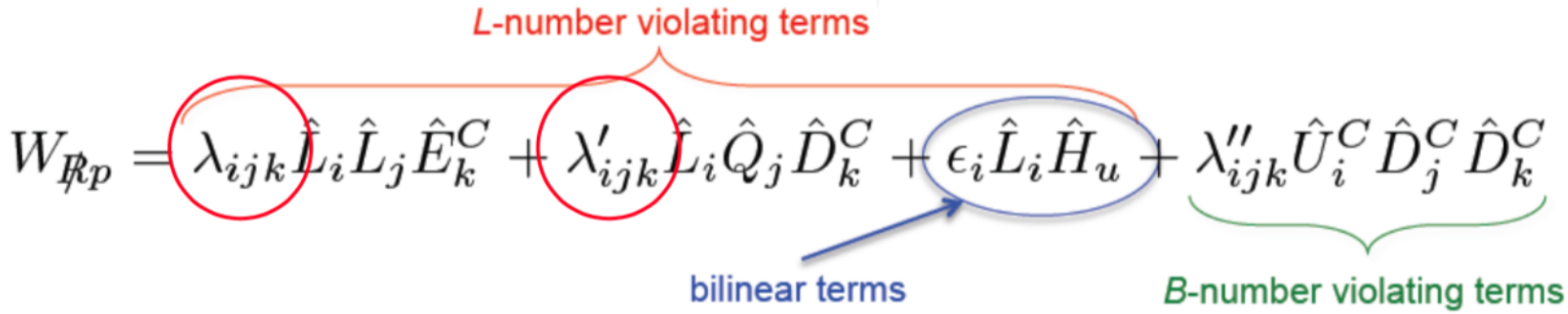




- Higgsino scenarios (mass degenerate, small cross sections)
- Wino/bino compressed (sleptons heavier than charg/neut)
- Promptly decaying or long lived (expecting short lifetimes)

R Parity violating SUSY

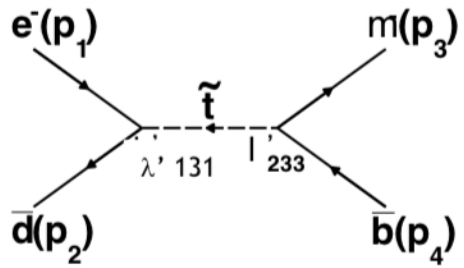
One of the most-often studied cases at ep up to now:



Various strong constrains from LHC on λ and λ'' *(from multilepton and multijet searches)*. At e-p colliders, studies made on stop and sbottom:

stop

http://arxiv.org/pdf/1107.4461v2.pdf



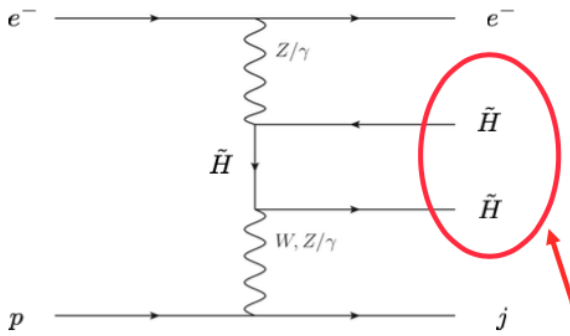
Couplings with third gen quarks
In e-p production rate depending on:
e-d-t: λ'_{131} (constraint: < 0.03)

Probe RPV LQD terms:
In this case $\lambda'_{131} \times \lambda'_{233}$

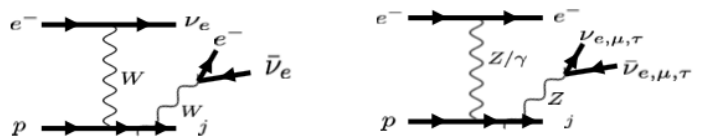
FCC-eh potential being re-evaluated:
(Ren-You Zhang, Liang Han et al)

Prompt Higgsino searches

Very difficult scenario to probe at pp. Han, Li, Pan, Wang, [arXiv:1802.03679]



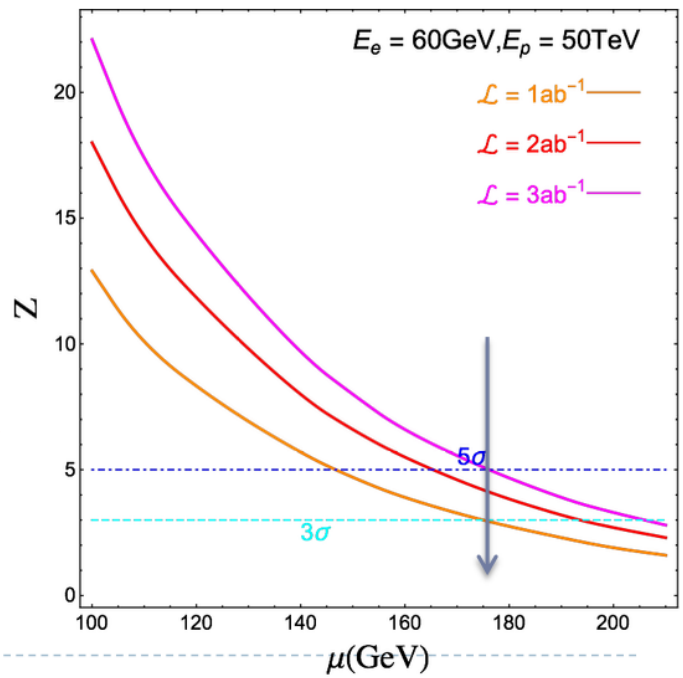
Typical signal: electron + jet + missing energy



Standard model main backgrounds

$$E_T^{miss} > 70 \text{ GeV}$$
$$5 \text{ GeV} < p_T^e < 25 \text{ GeV}, \ 1.0 < \eta^e < 5.0$$
$$p_T^j > 20 \text{ GeV}, \ -5.0 < \eta^j < -3.0$$
$$m_{ej} > 400 \text{ GeV}$$
$$y = \frac{k_p \cdot (k_e^{in} - k_e^{out})}{k_e^{in} \cdot k_p} > 0.2$$

preliminary result



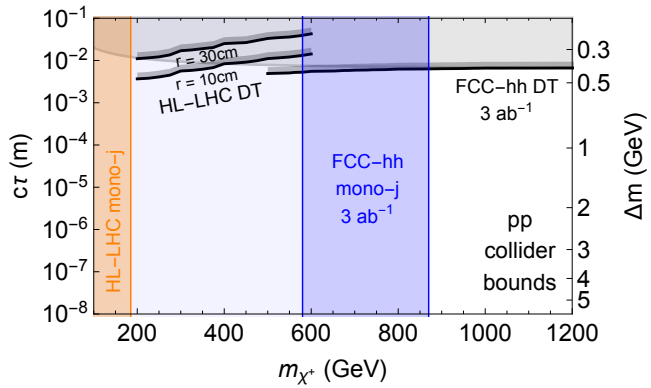
Long lived particles (LLP)

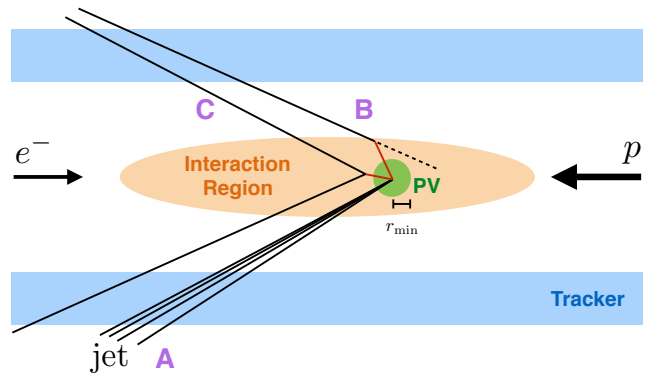
Excellent tracking resolution, clean environment and longitudinal boost offer great opportunity for detecting LLPs.

Long-lived Higgsinos

For details see talk by JZ on Thursday, WG3

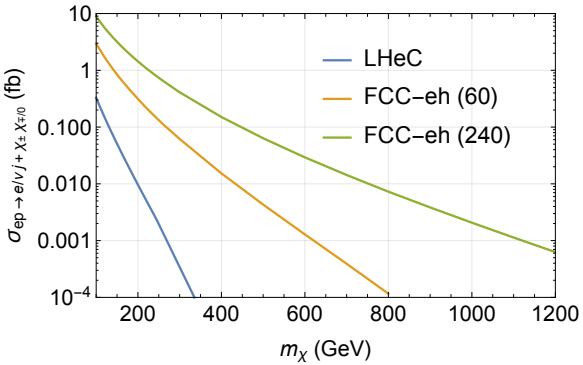
- LLP well motivated, e.g. approximate symmetries, sequestration of sectors.
- Higgsinos can be the LSP (neutralino$_1$).
- Many theories have natural LLPs:
  - WIMP Baryogenesis (Cui *et al.* [1212.2973])
  - FIMP DM (Hall *et al.* [0911.1120]),
  - Exotic Higgs decays (Curtin et al. [1312.4992]),
  - νMSM (Shaposhnikov *et al.* [0705.1729]).
- Spectacular new physics signals:
  - Monojet, monophoton, mono-Z, mono-Higgs searches.
  - Displaced secondary vertices.
  - Displaced or kinked tracks.

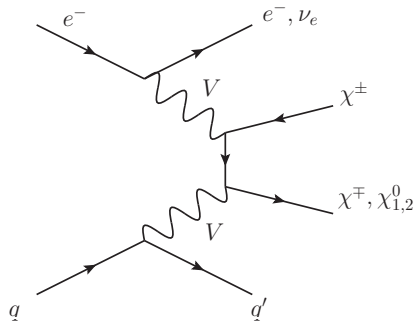




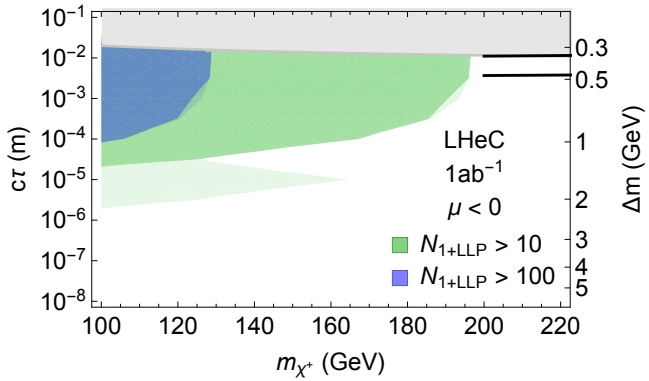
Discovering Higgsino LLPs in electron-proton collisions

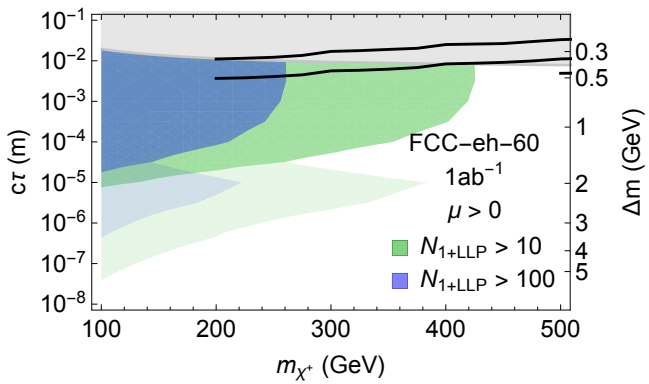
Curtin, Deshpande, Fischer, Zurita; [arXiv:1712.07135]





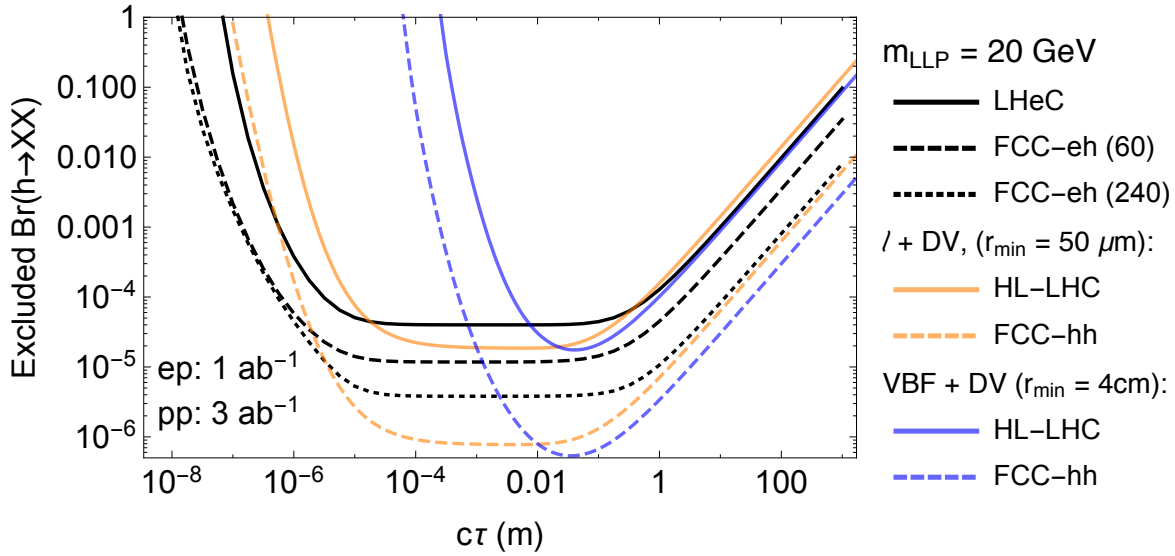
- Decay products $P_T = \mathcal{O}(100)$ MeV very short lifetime $c\tau \sim \mu$m
- Production via vector boson fusion
- Beam remnant jet $\Rightarrow$ primary vertex with $\mathcal{O}(10)\,\mu$m precision
- Signal: single soft displaced pion.
- Looks like hadronic noise, but can be detected at ep colliders!





1.1 TeV Higgsino (thermal relic DM) can be discovered with 240 GeV electron beams and 10/ab.

Exotic Higgs decays into LLPs



Curtin, Deshpande, Fischer, Zurita; [arXiv:1712.07135]

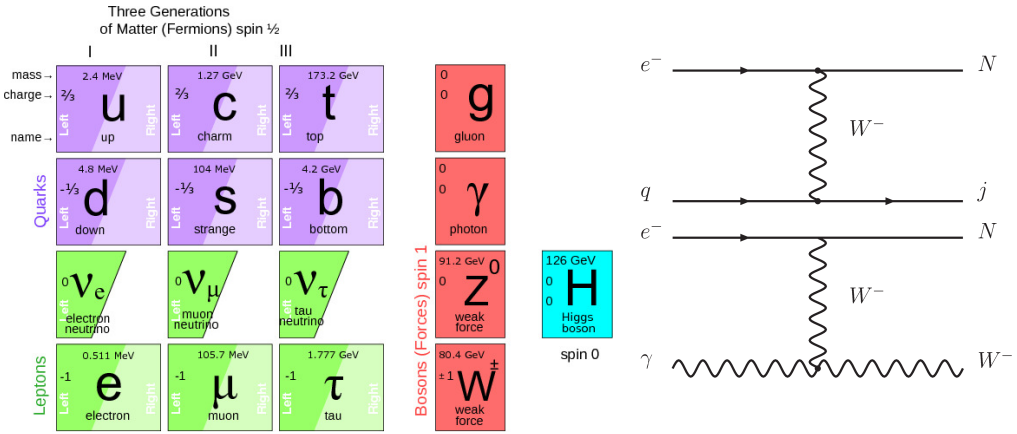
- Exotic Higgs decays are strongly motivated in general

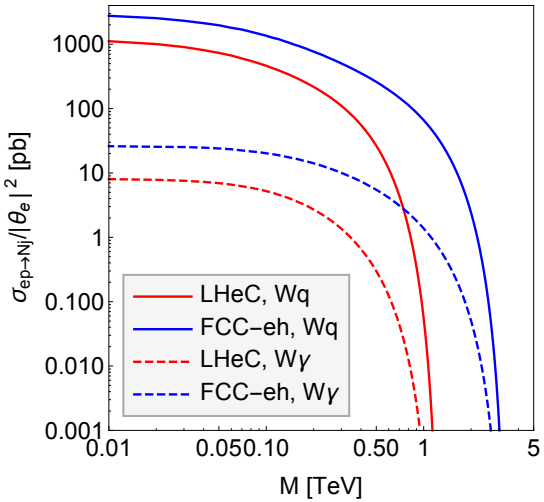
  Curtin *et al.*, Phys. Rev. D **90** (2014) no.7, 075004, [arXiv:1312.4992]
- Considered exotic Higgs decays into a pair of BSM LLPs X.
- Exotic branching fraction $\mathrm{Br}(h \to XX)$ and LLP lifetime $c\tau$ both free parameters.
- Assumption: $P_T > 400$ MeV, displacement $> 50\,\mu$m with 100% detection efficiency

Sterile Neutrino Searches

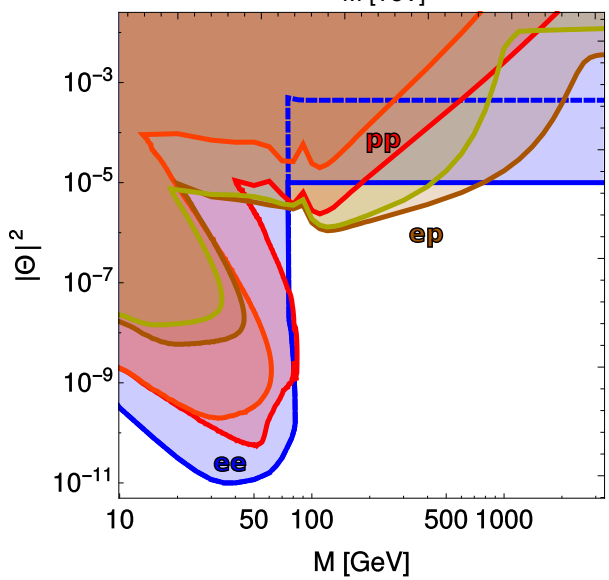
Sterile neutrinos at future electron-proton colliders

Antusch *et al.* Int. J. Mod. Phys. A **32** (2017) no.14, 1750078



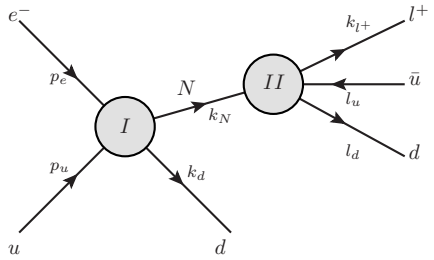


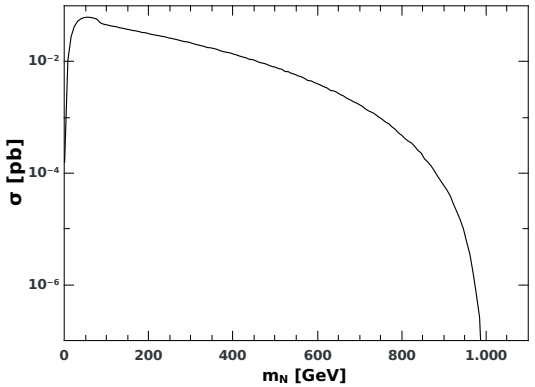
- Neutrino oscillations $\rightarrow$ type I seesaw
- Lowscale seesaw models allow large production xsections at colliders
- Constraints (active-sterile neutrino mixing electron flavor): $|\theta_e| \leq 10^{-3}$
- Searches via lepton-flavor violating final states: μ +jets, $\mu\tau$ + jets

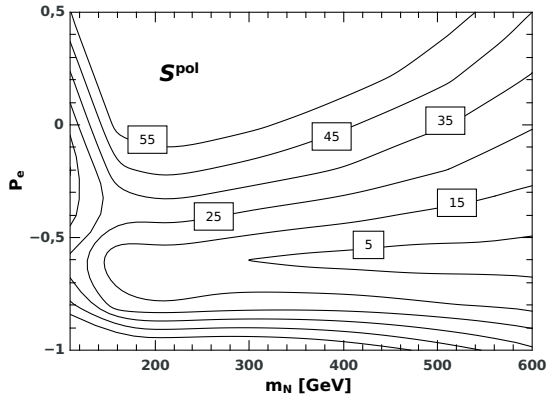


- Displaced vertex searches for heavy neutrino masses $< m_W$

Effective Majorana Neutrino Interactions and Polarization





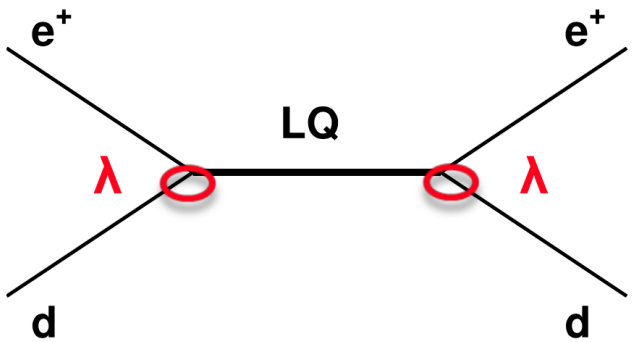


Duarte, Zapata, Sampayo; [arXiv:1802.07620]

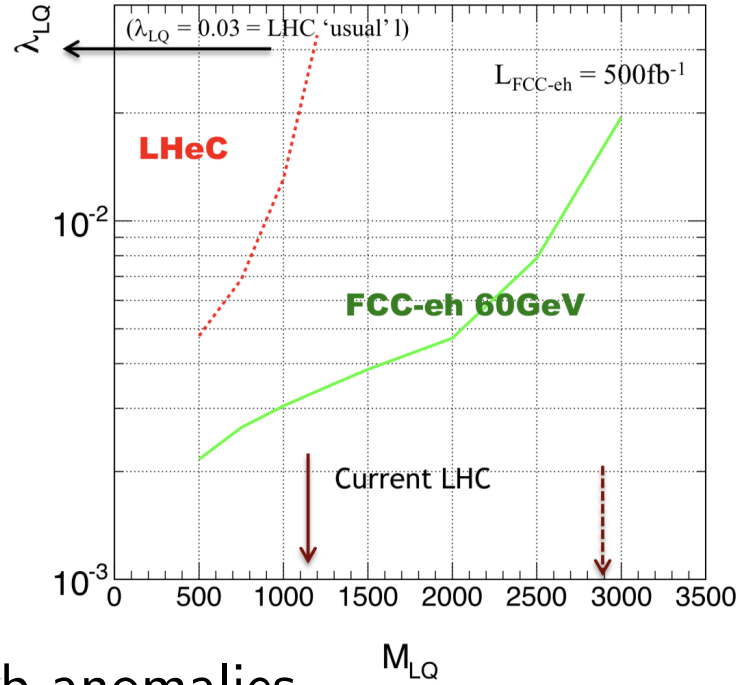
- Production of Heavy Majorana Neutrinos via new operators.
- These operators lead to a non-trivial Lorentz structure of the production process
- LNV final states are sensitive to the Lorentz structure via electron beam polarization.
- ep colliders allow to disentangle the vectorial and scalar operators contributions.

Leptoquarks

Leptoquark searches in electron-proton collisions



work by G. Azuelos



- Recent motivation from LHCb anomalies (theory explanations typically involve 3^{rd} generation).
- Phenomenology equivalent to R-parity violating SUSY.
- At pp: mostly pair production, single production possible.
- In ep collisions singly produced as s channel resonance.

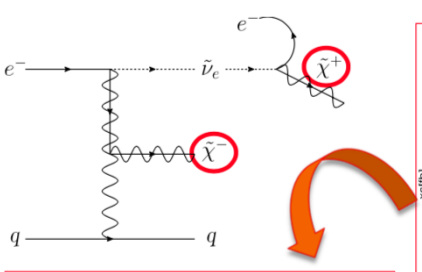
$\Rightarrow$ Very sensitive to 1^{st} generation.

$\Rightarrow$ Can measure: fermion number, flavor structure, spin, ...

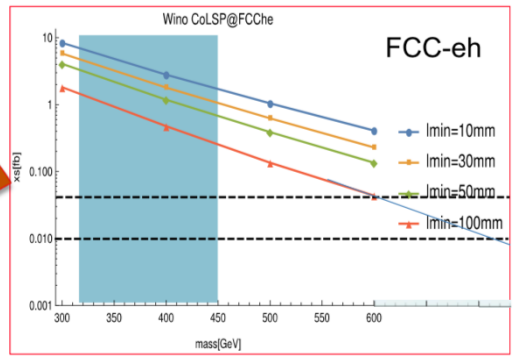
cf. also: Zhang, Yue, Liu; Mod. Phys. Lett. A **33** (2018) no.06, 1850039

Many more studies...

... too many for 20'

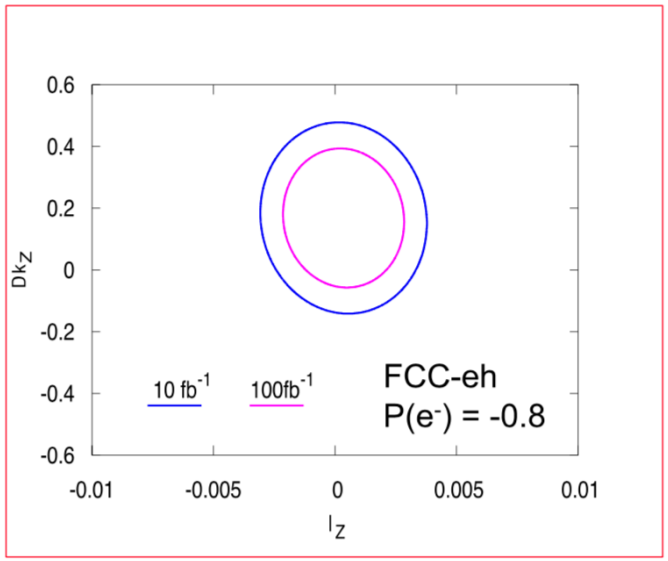


1 ab-1 @ FCC-eh:
$c\tau$ > 100 mm
~ 40 events for 600 GeV
~ 10 events for 750 GeV
excellent discovery potential



With no polarization;
$m_{\tilde{e}_L} = m_{\tilde{\chi}_1^0} + 9$ GeV

Sensitivities to anomalous couplings $\lambda_Z \sim 10^{-3}$



- Charged scalars in 2HDM models
- Light, long lived sleptons
- Anomalous gauge couplings
- Contact interactions
- ...

2HDM	X	Y	Z	$m_H^{\pm}$ = 110 GeV	
				cb	s $.cb$
Ia	5	5	5	0.99	97.36
Ib	5	5	5	0.99	99.80
IIa	32	0.5	32	0.99	92.00
Ya	32	0.5	0.5	0.99	75.12

Conclusions

- ep collider are complementary to pp and ee colliders. (Essential to fully exploit pp measurements due to PDF.)
- They offer a variety of opportunities for BSM searches.
- Ideal to study properties of new particles with couplings to electron-quark
- New opportunities for displaced signatures from LLPs:
  - Great reach for short lifetimes
  - Well suited to find signal that looks like hadronic noise.